UNUSUAL STARS

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16. Abstract

A discussion is given of eclipsing variable stars.
The unusual representatives of these stars are
analyzed, including the star RU Monocerotis, and
31 and 32 Cygni. Studies have shown that in
the chromospheres of these stars there are
condensations from 100 to 10,000 km in extent.

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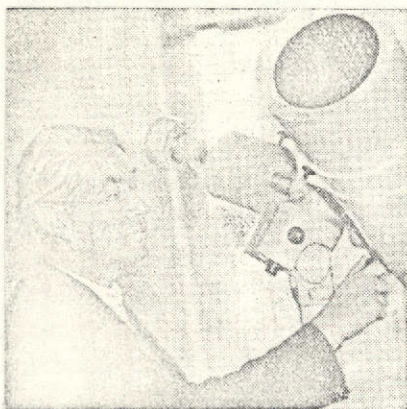
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The so-called eclipsing variable stars were known to astronomers already about 200 years ago. They are binary systems in which one star periodically blocks our view (eclipses) of the other as it revolves around the common center of mass, and then one-half period later, it is eclipsed in its turn by the other star. A typical example of such a system is the star Algol (β Persei). Its variability was discovered in 1669, and it was studied earlier than other eclipsing variable stars: a young Englishman, the amateur astronomer John Goodricke gave the correct explanation of Algol's brightness variations already in 1783.

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**Numbers in the margin indicate pagination of original foreign text.

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More than 4,000 eclipsing binaries are now known. Many astronomers and amateur astronomers are busy observing them. This much is understood: the analysis of the light curve of such a star and its spectrum permit the determination of the most varied characteristics of the system — the dimensions and shape of its components, their masses and densities, the surface temperature, the dimensions and shapes of the orbits, and the orbital velocities.

Usually, the brighter of the system's stars is denoted as the primary star, while the less bright star is denoted as the companion, although the cold and faint companion is often larger than the primary star. The time of minimum brightness during the eclipse of the primary star is called primary minimum, and the time of the eclipse of the companion is called the secondary minimum. Some stars have a secondary minimum located not exactly halfway between two primary minima but shifted to one side. This indicates that the companion's orbit is not circular, but elliptical. Near periastrom — the point in its orbit nearest to the primary star — the companion moves more rapidly than near apoastrom — the most distant point in its orbit, in agreement with Kepler's second law. Therefore, the companion passes from primary minimum I to secondary minimum II in less time than from the minimum II to the next primary minimum III (Figures 1 and 2).

From the point of view of their physical structure, eclipsing variable stars are not anything special: they are stars which are the major components of binary and multiple systems. Those of them whose arbital plane is slightly inclined to the line of sight are observed by us as eclipsing variables. But there are rather interesting and even unusual
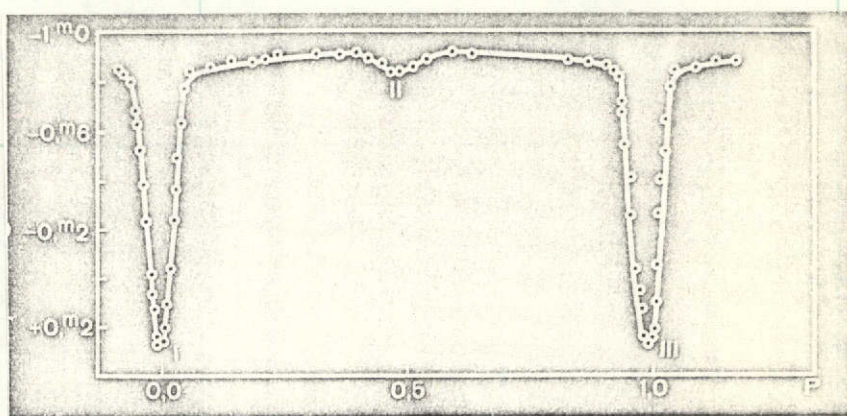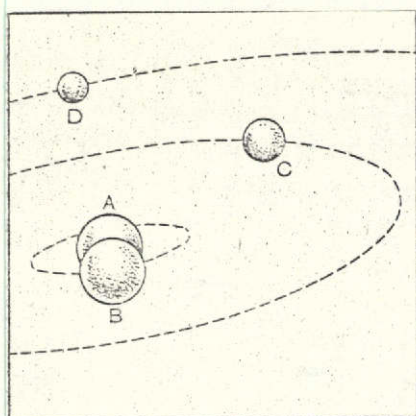
Figure 1. Algol (β Persei) multiple star from the point of view of a terrestrial observer and its light curve.

A- primary star; B- companion; stars C and D do not participate in the eclipse phenomenon, but oscillations in the period of the brightness variation are caused by their attraction. Time in fractions of the period P is plotted on the graph along the abscissa, and the decline in brightness is plotted along the ordinate in stellar magnitudes; I and III denote the primary minima, and II denotes the secondary minimum.

representatives among the stars. We would like now to talk about them.

The Strange History of the Star RU Monocerotis

The variability of RU Monocerotis' brightness was discovered at the beginning of our century by the Russian investigator of variable stars, L. P. Tseraskaya, on photographs of the Moscow Observatory. Already in 1905, an astronomer of that same observatory, S. N. Blazhko, established that this rather faint star (stellar magnitude of 10.5 at maximum) was an eclipsing binary in which an eclipse occurs every 21 hours and 30.5 minutes.
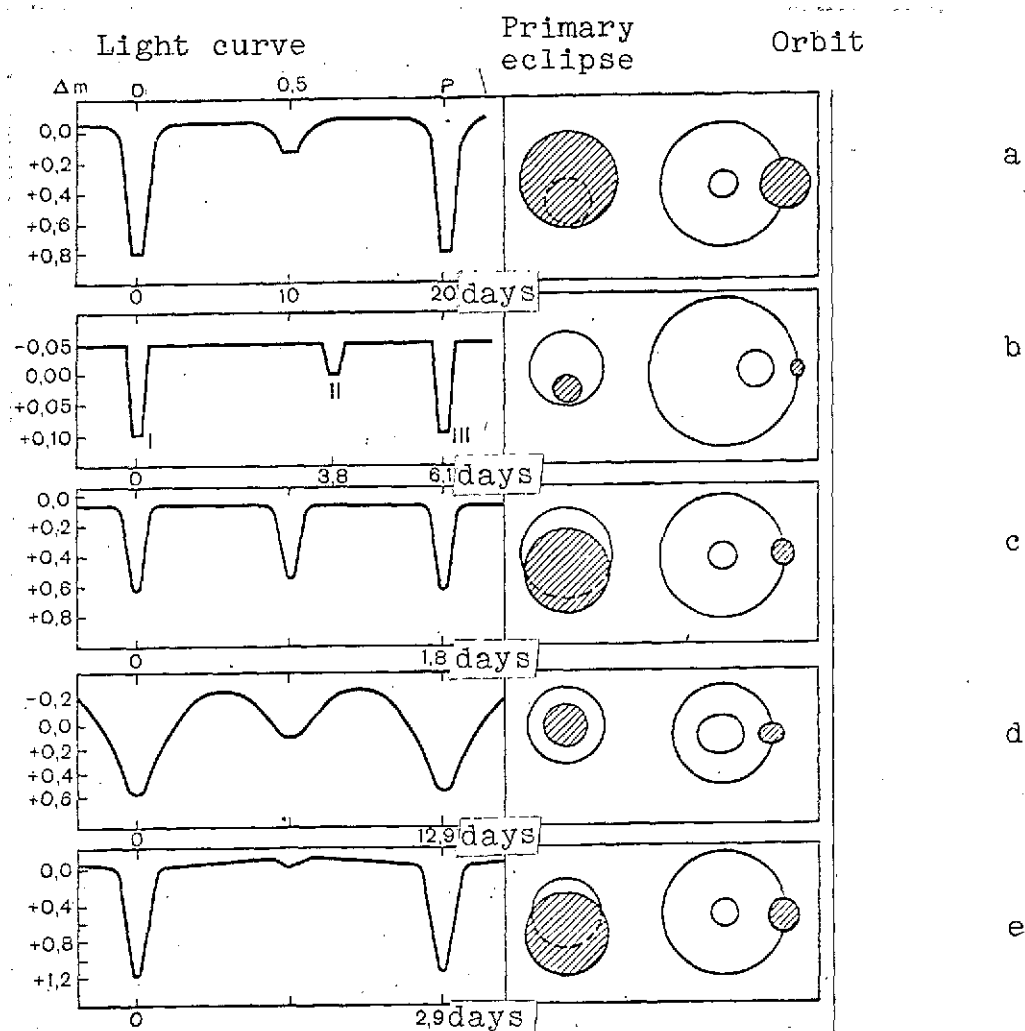
Figure 2. Light curves of various eclipsing variable stars, their shapes during the primary eclipse (for a terrestrial observer), and the layout of their orbits.

a- AR Lacertae (total eclipse, circular orbit); b- IH Cassiopeiae (annular eclipse, elliptical orbit, and secondary minimum shifted); c- RX Herculis (partial eclipse, circular orbit); d- β Lyrae (ellipsoidal stars forming a close pair, annular eclipse; and e- β Persei (partial eclipse, circular orbit, the effect of the reflection of one star's light from the other is noticed, which causes a rise in the light curve from the primary minimum to the secondary).

Two decades passed by. In the middle of the 1920's,
Blazhko again returned to observations of RU Monocerotis and
was amazed: its period had changed by 3-1/2 hours, becoming
25 hours and 4 minutes. Two years later, it was explained that
the new observations did not agree with this period, nor that   <u>/80</u>
obtained in 1905. The star was clearly behaving somewhat
strangely.

At Blazhko's suggestion, young Kazan' astronomers A. D.
Dubyago and D. Ya. Martynov conducted a more extensive series
of observations of the star. Over a period of one year
(1927 — 1928), they made about 400 brightness estimates for
RU Monocerotis and "discovered" a period of 3.58 days after
which the brightness minima necessarily repeated themselves.
But other minima occurred in the interval between these
"primary" minima and, as it first appeared, at random.

Martynov and Dubyago noticed that the period obtained by
Blazhko in 1905 was exactly 1/4 of the period of 3.58 days.
The key to the mystery of the behavior of this star had been
found. Its true period was equal to 3.58 days, but both stars
were almost identical, and the secondary minima did not differ
at first glance from the primary minima. It became clear that
the star's orbit was highly elongated (has a large eccentricity),
and therefore the secondary minima were shifted in a direction
away from the midpoint between primary minima, as shown in
Figure 2b. But the most significant thing consisted of the
fact that the major axis of the orbit (the line of apsides)
was slowly rotating in the plane of its own orbit, because the
intervals between successive minima were changing with the
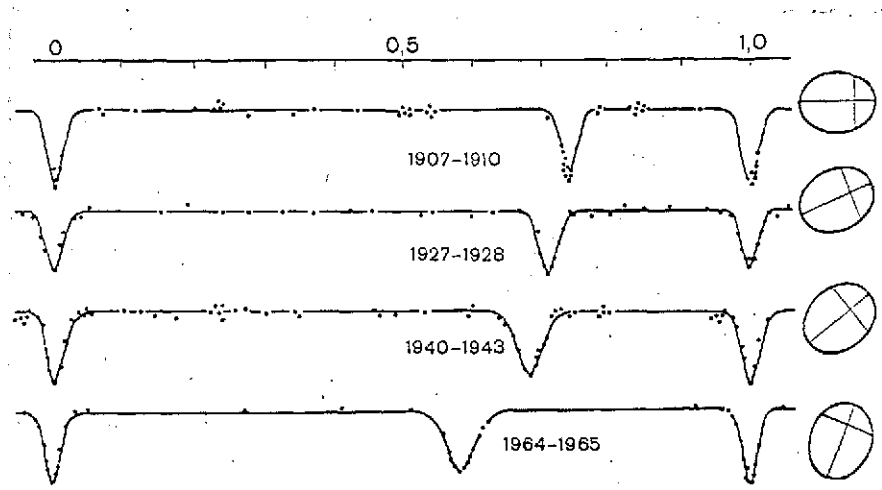years (Figure 3).

Figure 3. Variations in the light curves of the star RU Monocerotis caused by the revolution of its line of apsides (illustrated on the right). Each curve is labeled with the years of the observations, and the fractions of a period are indicated on the upper scale. (Only the displacement of the secondary minimum relative to the primary is shown. Actually, both minima are displaced in different directions by the same amount.)

The phenomenon of the rotation of the line of apsides was already known long ago for the Moon orbit. As the theory of this phenomenon showed, the size of the shift depends on the equatorial compression of the central object and on the mass distribution law within it, in other words, on the density distribution law with depth.

According to the theory of the internal structure of massive gaseous spheres (which stars are) developed already in 1907 by the German theoritician R. Emde, the pressure p inside a star increases with the increasing density ρ according to the law:

$$p = K\rho^{1+\frac{1}{n}}.$$

Such a relationship, when the pressure p is proportional to some power of the density ρ, is called a polytropic relation,

and the quantity n is the polytropic index. It plays an important role in the theory of the internal structure of stars and also in the structure of stellar and planetary atmospheres (n = 5/2 for the terrestrial atmosphere).

The English astronomer T. Sterne proved, in 1939, that the rate of rotation of the line of apsides depends on the polytropic index. It is true that each of the stars may have its own density distribution, and in order to obtain a completel solution of the problem, it is necessary to know the radii and masses of the stars, the distance between them, and primarily the eccentricity of the orbit.

New observations were necessary. The star RU Monocerotis is best viewed in the northern hemisphere in the winter. Thus, in January of 1940, D. Ya. Martynov began a new series of observations. In 1961, a coworker at the Odessa Observatory, A. Ye. Prikhod'ko, reduced all the existing observations from 1905 through 1960 and found that the orbital eccentricity was equal to 0.41 and a complete revolution of the line of apsides takes place in 430 years.

In November of 1964, the possibility occurred to Martynov to carry out investigations of the star under far more favorable conditions than exist in the northern hemisphere, namely, at the Mount Stromlo Observatory (Canberra, Australia), which is located at southern latitude 35°, where it is possible to observe RU Monocerotis with a culmination 24° from the zenith. In addition, summer begins in Australia in November-December.

The Australian astronomers placed at Martynov's disposal a 50-inch reflector equipped with a photomultiplier as the radiation receiver. He obtained, with this telescope and with

the 40-inch reflector of the Saiding Spring Observatory (500 km north of Canberra), the most valuable observation from the standpoint of accuracy in three spectral regions and reduced anew all the accumulated data.

It was clear that, due to the rotation of the line of apsides (see Figure 3), not only are the epochs of both minima shifted, but their duration is altered. Thus, in 1964 — 1965, when the orbit was turned with the apoastrom towards the Earth, the secondary minimum, which occurred near apoastrom, lasted two times longer than primary minimum, which occurred near /82 periastrom, where the companion star passed nearer to the primary star and, therefore, moved more rapidly. A comparison of the duration of both minima and the shift of the secondary minimum with respect to the midpoint between two primary minima permitted finding the orbital eccentricity and the longitude of periastrom. The eccentricity was found to be 0.376, and the rate of rotation of the line of apsides corresponded to its complete rotation every 284 years.

Recently, in 1971, the Rumanian astronomer I. Todoran reduced anew all the observations of the star and found that the period of rotation of the line of apsides might vary, being 436 years up to 1940 and 330 years thereafter. He found the eccentricity to be 0.40 — 0.39.

In order to calculate the internal structure of the components of the RU Monocerotis system, it was now necessary only to determine their masses and radii. The spectrum of this

star belongs to the spectral class* B9, and broad hydrogen lines are visible in it. Usually, in the spectra of binary systems, a doubling of the spectral lines is observed, in agreement with the Doppler effect, due to the motion of the components with respect to the line of sight. But, in RU Monocerotis' spectrum, the lines are not split into two components, but are only broadened. The American astronomer O. Struve found, from the magnitude of the broadening, that the velocity of each of these stars in orbit is equal to 128 km/sec, and this means that the velocity of their relative motion is 256 km/sec. The dimensions of the orbits were determined from the velocity and period of revolution, and it was not difficult to find from the orbital dimensions and the period (on the basis of Kepler's third law) the masses of both stars and then (from the duration of the eclipses) their radii and densities. Both stars turned out to be white giants with masses of 2.4 — 2.5 $M_\odot$, radii of about 2 $R_\odot$, and average densities almost four times less than the solar value.

Now it was necessary to compare the derived results with the theory of the internal structure of stars. According to the theories, the ratio of the apsidal period U to the orbital period P was determined as the product of two factors, of which

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*The following spectral classes of stars have now been adopted in astronomy: O— the hottest blue stars (temperature up to 100,000°); B— bluish-white stars (15,000 — 30,000°); A— white stars (10,000°); F— yellowish-white stars (8,000°); G— yellow stars (6,000°); K— orange stars (4,500°); M— red stars (3,000°). Each spectral class is divided into ten sub-classes, for·example: B0, B1, B2, ..., B9. Our Sun is a typical representative of spectral class G.

one depends on the masses and radii of the stars and the
orbital eccentricity, while the other depends on the model of
the star internal structure, i.e., on the polytropic index.
For the RU Monocerotis system, the first factor was equal to
approximately 1000; the second factor was computed for poly-
tropic indices of n = 2, 3, and 4 and for the ratios of the
central density to mean density ρ_c/ρ_m corresponding to them.

The theoretical values of U/P lay between 4650 (n = 2) and
263,000 (n = 4). And what do the observations give? For
different values of the period U, the ratios U/P lay within
the range from 29,000 to 44,000, whence values of the polytropic /83
index n from 3.08 to 3.23, and ratios of ρ_c/ρ, from 65 to 85,
resulted.

Thus, independently of which solutions are closer to the
truth, it is obvious that the stars in the RU Monocerotis
system are constructed primarily according to a polytropic
law with an index n close to 3, i.e., the pressure in them
increases in proportion to the density raised to the 4/3 power,
and the central density is 65 — 85 times larger than the
mean density. We note for comparison that the Sun has n = 3/2,
in other words, the pressure within the Sun interior is
proportional to the density raised to the 5/3 power, but the
central density is also 65 times larger than the mean density
since the Sun radius is smaller than that of RU Monocerotis.

The star RU Monocerotis is not unique among those for which
rotation of the line of apsides [has] been observed. Eight
such stars are known. Four have a comparatively short apsidal
period: from 25 to 72 years. Two of them — Y Cygni and GL
Carinae — have been studied rather thoroughly. The components
of Y Cygni are class B0 supergiants with masses of 17 $M_\odot$ each.

Stars of the system GL Carinae are almost similar blue super-giants. Investigation of them is facilitated by the fact that already 2 — 3 complete apsidal rotations have occurred since these stars were first observed. Their structure also agrees well with theory. The five remaining stars have been poorly studied. For three of them, the rotation period of the line of apsides is measured in hundreds of years, just as for RU Monocerotis. Nevertheless, it is necessary to observe them. In fact, the history of the persistent investigation of the star RU Monocerotis clearly showed us how it is possible to construct a model of the internal structure of a star on the basis of purely external characteristics, namely, the variation in the brightness and spectrum.

Stars with Extended Atmospheres

In the constellation Auriga, a bit to the right of the bright Capella, which adorns our winter sky, there are visible three faint little stars forming an isosceles triangle. The upper star (the nearest to Capella) has received the designation ε (epsilon), and the lower right star is denoted as ζ (zeta). They have both proven to be of interest due to their rarity.

ζ Aurigae is a rather bright star by astronomical standards (fourth stellar magnitude) and for a long time, it was generally not considered to be a variable star. In 1897, E. Maury, at Harvard Observatory, began to study its complex spectrum: lines characteristic of hot class B stars and of cold class K stars are present in it. In 1908, the American astrophysicist W. Campbell established that this star was a spectroscopic binary. This still did not mean, however, that it was an eclipsing binary: in fact, the orbit of the companion might be projected above or below the primary star. But 16 years

later, the Canadian astronomer W. Harper noticed that on one
of the spectrograms taken at an epoch when, according to the
orbital elements which he calculated, the K star was in front
of the B star, the lines of the latter were not
visible. This gave the basis for the German astronomer
K. Bottlinger to assert that ζ Aurigae was an eclipsing variable /84
star. But this fact was finally established only in 1932 by
the German astronomers P. Gutnik and G. Shneller, who were the
first to observe an eclipse of the B star by the K star and
to determine the dimensions of both stars. Why was the vari-
ability in the brightness of such a bright star not noticed
for such a long time? There are essentially two reasons here.
In the first place, eclipses of ζ Aurigae occur rather rarely:
once every two years and eight months (972 days). In the second
place, the drop in brightness is small: only 0.125 stellar
magnitudes in the visual region. It is true that the amplitude
of the brightness decrease in the photographic region is already
0.5 stellar magnitudes,* but the eclipse occurs very slowly:
the partial phase lasts 1.3 days, after which the total phase
continues for 37 — 38 days. Thus, one observer cannot capture
the entire partial phase — cooperative observations by a number
of observers located at various longitudes are necessary to
accomplish this. We will show later on what such observers can
contribute.

Thus, it was not a simple matter to obtain data about the
orbits and masses of both stars. Yet, Harper was able to
determine, in 1927, from the shift in the lines of the K star,
the semimajor axis of its orbit — 294 million kilometers. But
it turned out to be significantly more difficult to find the
size of the orbit of the B star, since the lines of the K star

*The size of the brightness decrease depends, as it is
easy to guess from the star's color, on the color system in
which the observations are made. The bluish B star emits more
blue radiation, to which a photographic plate is sensitive, and
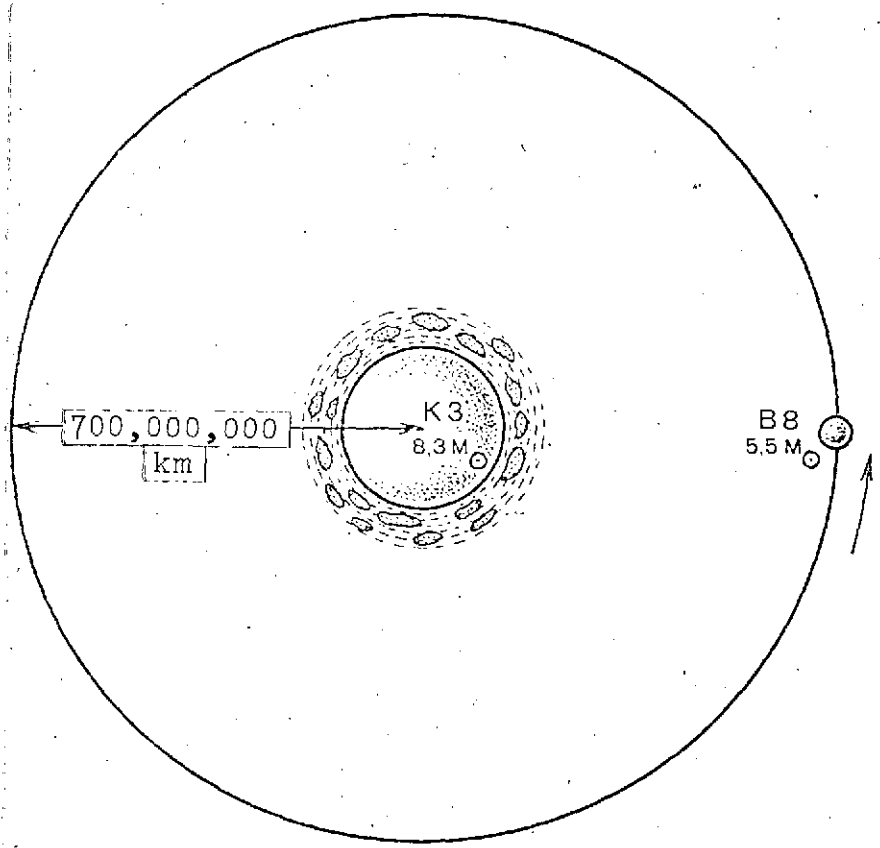less yellow-green radiation, which is received by the eye.

Figure 4. The system of the star ζ Aurigae. Its extended atmosphere with clouds and clumps is shown.

were superimposed on the hydrogen lines (unique to its spectrum). Without knowing the dimensions of both orbits, it was impossible to determine the masses of the components. Gutnik and Shneller greatly overestimated both masses and their ratio. The values obtained have gradually been refined, and as of the present time, we represent the system ζ Aurigae in the following form (Figure 4).

The primary star is an orange supergiant of class K3 with a mass of 8.3 $M_\odot$ and a radius of 200 $R_\odot$ (140 million kilometers, in other words, slightly smaller than the radius of the Earth's

orbit). At a distance of 700 million kilometers from the primary star (almost as far as Jupiter is from the Sun), there is revolving a companion, which is a white-bluish giant of class B8 with a mass of about 5.5 $M_\odot$ and a radius of "only" 3.7 $R_\odot$ (2.6 million kilometers). The companion completes a complete revolution about its orbit in 972 days, as has already been stated.

However, the attention of astronomers has by no means been attracted to this system by its gigantic scale and not at all by the history of its discovery and investigation. The most interesting peculiarity, which has forced astronomers to segregate ζ Aurigae into a special class of stars, has been discovered upon a detailed study of its spectrum.

In 1934, the American astronomers W. Christi and O. Wilson noticed that the spectrum of the star undergoes complex changes in the course of the eclipse which it is not possible to explain just by the geometrical layout of the eclipse (Figure 5). At the very beginning, even prior to the onset of the eclipse, the H and K lines of ionized calcium appear in the spectrum of ζ Aurigae in addition to the strong hydrogen absorption lines belonging to the white-bluish B giant. The K line is especially distinguished because the H line is superimposed on the H_ε hydrogen line. The hydrogen lines are strengthened, although it would appear due to the occultation of the B component that they should weaken! Nevertheless, lines of the ions of titanium, scandium, chrome, iron, and other metals, and somewhat later lines of the neutral metal atoms, appear and grow stronger. (Such a spectrum is characteristic of the chromosphere of the Sun, and it has become customary to call it a chromospheric spectrum.) Sometime later on, an abrupt change sets in. The
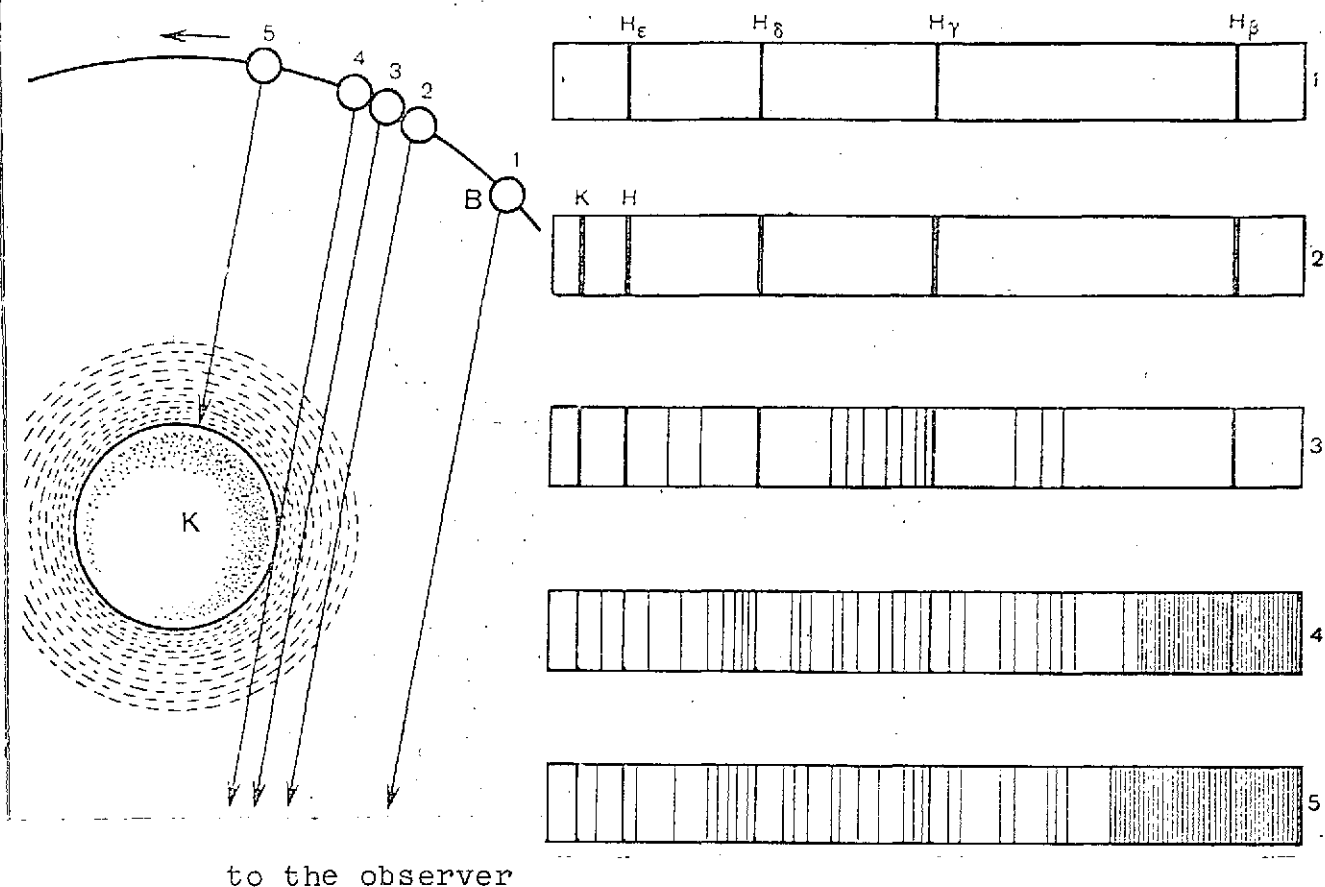
to the observer

Figure 5.   Path of the light rays of the B star through the extended atmosphere [of] the K star in the system ζ Aurigae and a schematic diagram of the variation in its spectrum.

1- no eclipse; the lines of the Balmer series of hydrogen belonging to the B star are visible in the spectrum;   2- light rays of the B star pass through the upper layers of the chromosphere of the K star, and the H and K lines of ionized calcium appear;   3- other chromospheric lines appear in the spectrum; 4- due to strong absorption, chromospheric lines and the continuous spectrum of the B star fade, and the lines of the spectrum of the K star become visible;   5- total eclipse; the spectrum of the B star disappears, and the lines of the spectrum of the K star, drowned out earlier in the continuous spectrum of the B star, are easily visible.

chromospheric lines weaken, the lines of the B star simultaneously become fainter, and the spectrum of the K component is strengthened. Finally, a total eclipse begins. The lines of the B star disappear and there remains the typical spectrum of a K supergiant with numerous absorption lines mainly of the metals.

Back in the 1930's, the hypothesis arose that the K star has an extended atmosphere which begins the eclipse. Soon the hypothesis received confirmation: in ultraviolet light (which is absorbed most strongly by the atmosphere), the eclipse begins earlier than in blue light, and in blue light earlier than in yellow-green light. All the complex variations in the spectrum of the star during the partial eclipse have thus been explained by the passage of the light of the B star through the atmosphere of the K star and absorption in it. Thus was discovered a new type of star: stars with extended atmospheres.

The stars 31 and 32 Cygni are very similar to ζ Aurigae. They are both of fourth stellar magnitude and are located next to each other in the sky. The primary stars in both systems are orange supergiants of spectral classes K3 and K5, with a mass of about 20 $M_\odot$, and the companions are white giants of spectral class B3 with a mass of 7 — 9 $M_\odot$. The revolution period of 32 Cygni is about 3 years, and that of 31 Cygni is about 10.5 years. 31 Cygni has an almost central eclipse, just as does ζ Aurigae; 32 Cygni has, on the contrary, an almost tangential eclipse; therefore, its partial phases last longer and its total phase is shorter than for the other two stars (Figure 6). The membership of both stars in the ζ Aurigae type was established in 1944 by the American astronomer D. McLaughlin.
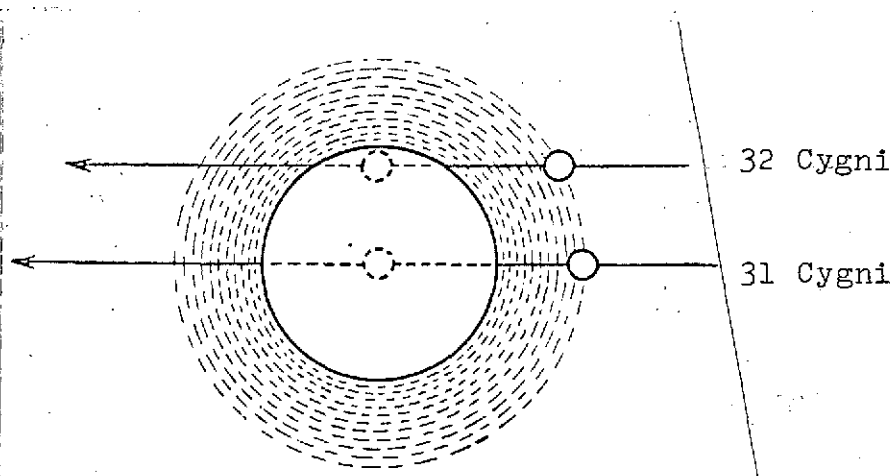
Figure 6. A schematic diagram of a central and a tangential eclipse by the stars 31 and 32 Cygni (from the point of view of a terrestrial observer). The partial phase of the eclipse of 32 Cygni lasts longer than the total phase shorter than for the 31 Cygni.

Careful investigations of the chromospheres of all three stars have shown that they are very extended, matching the largest stars: the chromosphere of 32 Cygni extends to almost 100 million kilometers, while that of 31 Cygni extends twice as far. The extent of the chromosphere of ζ Aurigae was found to be different at different eclipses: from 30 to 85 million kilometers.

The study of the intensities of the chromospheric lines has shown that there are, in the chromospheres of these stars, condensations from 100 to 10,000 km in extent and rapidly moving gigantic clouds similar to solar prominences, only far larger — up to 10 million kilometers. The space between the components of the stellar system is also filled with gas clouds, since small brightness oscillations are observed outside of the eclipses.

In addition to the three stars which have been described, it has proven possible to detect four others which may also belong to this type. We will discuss one of them later on — a neighbor called Zeta in the constellation, star ε Aurigae. Another one is the famous red supergiant VV Cephei. This star, which exceeds the Sun's diameter by a factor of 2000 (its diameter is as large as the orbit of Saturn), is visible, however, only through binoculars (stellar magnitude 6.5). Its companion is a white giant of spectral class B9; eclipses occur once every twenty years and last for 16 months. After 1936, when McLaughlin first observed an eclipse of this star, it has proven possible to observe only two eclipses. But even prior to the establishment of the fact that the star VV Cephei is an eclipsing binary, it was clarified that the red supergiant itself is a physical variable star,* which varies in brightenss in an irregular way.

Observations of stars with extended atmospheres have given astronomers the rare possibility of studying the chromospheres of other stars of a different type than the Sun and have shown details in them resembling clouds or prominences. This has made a significant contribution to our ideas about the structure of stellar atmospheres.

The Puzzle of the Star ε Aurigae

Let us now turn to the star ε Aurigae. This star is truly unusual, and it may turn out that further study of it will result in discoveries of essential significance.

The German amateur astronomer G. Frich observed the variations in its brightness already in 1821. In 1847 — 1848,

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*Physical variable stars, in contrast to eclipsing variable stars, vary in brightness due to physical processes taking place in the star itself (usually pulsations).

the German astronomer F. Argelander noticed that its brightness dropped by a whole stellar magnitude: from $3^{m}\!.4$ to $4^{m}\!.4$, but then it brightened again to its previous value. In subsequent years, only faint irregular brightness variations were observed. A new weakening in its brightness was noticed in 1875. It was classified as an irregular variable and considered thus until 1901 — 1903, when a weakening in its brightness set in along with a simultaneous variation in the velocity of the star with respect to the line of sight. This made it possible for the German astronomer G. Ludendorff to draw the correct conclusion that ε Aurigae is an eclipsing variable star with a very long period. Actually, the period of this star is equal to 27 years. The duration of the eclipse is 71^{4} days (almost two years), including the duration of the total eclipse of 330 days.

There have been three eclipses of this star in all in the twentieth century: in 1901 — 1903, 1928 — 1930, and 1955 — 1957. Not only photometric but also spectroscopic observations have been carried out all three times. Some strange circumstances have been discovered.

The spectrum of the star indicated that it is a yellow supergiant of spectral class F. No other lines which might be assigned to the secondary component of the system were observed in the spectrum of the star. During the eclipse, the intensity of the absorption lines arising upon the passage of the light of the F star through its atmosphere strengthened, strange as this may seem, while the continuous spectrum weakened by almost a factor of 2. In addition, a splitting of the lines was observed.

It was clear that the F supergiant was being eclipsed and
was not the eclipsing star. This conclusion followed from the
fact that only its spectrum was observed. But what star causes
the eclipse? The extensive period of constant light in the
middle of the eclipse indicates that the eclipse is either
total or annular (a small star covers a large one). But if
the eclipse were annular, then a total eclipse should occur
approximately one-half period later, when the large star covers
the small one. In addition, it should be assumed that both
stars belong to the spectral class F. The duration of the
main phase of the eclipse indicated a large difference in sizes
of the components, but it is not observed in the spectral class
F. Nevertheless, all three eclipses of the twentieth century
were accompanied by completely identical variations in the
spectrum; therefore, it is in no way possible to assume that
we are observing an annular eclipse followed one-half period
later by a total eclipse (i.e., that the true period is equal
to 54 years). The main problem is how to explain the strengthen-
ing of the absorption lines?

If we assume that, once every 27 years, the F supergiant
is covered by another star, it should, in the first place, be
enormous and, in the second place, very faint (there are no
secondary minima!) and, thirdly, it should be transparent (the
spectrum of the F star is visible even during the total eclipse).

Before we discuss the hypotheses which have been put
forward to explain these properties of the eclipsing star, let
us calculate the ratio of the diameters of the components. It
is not difficult to make this calculation. As is evident from
Figure 7, the duration of the first half of the partial phase
$T_p/2$ (from position 1 to position 2, i.e., the time to
cover the smaller star) is proportional to the diameter of the
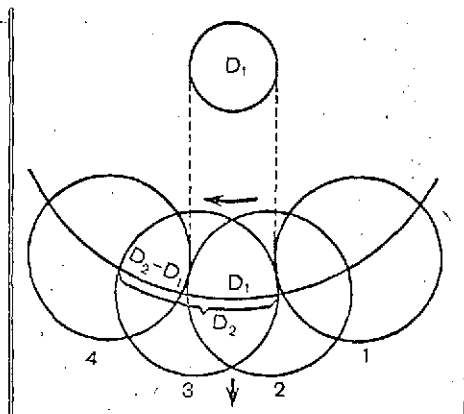
Figure 7. Schematic diagram of the eclipse of ε Aurigae.

D_1 and D_2– diameters of the components; 1, 2, 3, 4– the successive positions of the eclipsing star.

smaller star D_1. The duration of the total phase T_t (from position 2 to position 3) is proportional to the difference in the diameters of the larger and smaller stars $D_2 - D_1$. Thus, we obtain the equation:

$$\frac{T_p/2}{T_t} = \frac{D_1}{D_2 - D_1},$$

from which we find $D_2/D_1 = 2.7$.

The dimensions of the F supergiant determined from its luminosity and spectral class should be almost 1000 times larger than the dimension of the Sun. This means that the larger star exceeds the Sun by almost a factor of 2000. What is the nature of this puzzling star?

In 1937, astronomers of the Yerkes Observatory (USA) G. Kuiper, B. Stromgren, and O. Struve advanced a rather original hypothesis. Since the larger star has too low a temperature to contribute radiation in the visible spectrum, this means that it is an infrared star (I in Figure 8a). It consists of tenuous gaseous material which only partially absorbs the light of the F star. The ultraviolet radiation of the latter causes strong ionization in the layers of the I component turned towards it, and there is formed there something similar to our ionosphere. The scattering of the light of the F star by free electrons in the ionosphere of the I star produced the observed weakening in the brightness of ε Aurigae. Kuiper calculated that the temperature of the
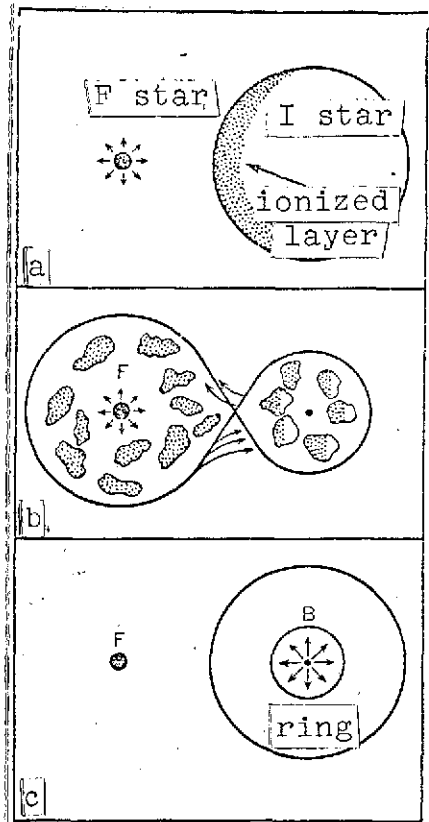
Figure 8. Three hypothetical models of the structure of the system ε Aurigae.

a- the model of O. Struve, G. Kuiper, and B. Stromgren (1937); F- primary star (supergiant of class F); I- large infrared star which causes the eclipse; b- O. Struve's model (1955). The companion of the F star is an invisible star of small dimensions; both stars are surrounded by a system of clouds which absorb the light of the F star; c- M. Hack's model (1961). The companion of the F supergiant is a hot class B star with a radius of 15 $R_\odot$, surrounded by an envelope one billion kilometers in extent.

I star is about 1000°. This means that it should radiate in the infrared region. However, attempts to detect its infrared radiation undertaken by Kuiper himself and J. Felgetp have not met with success. In addition, the German astronomers M. Shenberg and B. Young have proven that the density of the electron gas formed in the ionosphere of the I star due to ionization by the radiation of the F component is insufficient to produce the observed absorption of the light of the bright star.

Searches for another explanation have begun. Suggestions have been advanced that the absorption is caused by a cloud or ring of dust particles occupying the same volume as the hypothetical I star and surrounding a comparatively small companion of the F star.

The main requirement imposed on any serious scientific hypothesis is its ability to give a complete explanation of the entire set of observed

phenomena. The investigation of the star ε Aurigae was a
beautiful example of a long and persistent scientific search
which did not always result immediately in success.

In 1955, O. Struve suggested a new model for the star
ε Aurigae. According to this model (Figure 8b), there is no
I star; the companion is an invisible star of small dimensions
surrounded by an enormous cluster of gaseous clouds which are
moving in various directions at high velocities. In each
cloud, there is a thin layer turned towards the F supergiant,
and it is ionized by its radiation and absorbs light, according
to Stromgren's model. In order to explain the observed splitting
of the lines, Struve suggested that the F star itself is sur-
rounded by a similar system of clouds and that streams of gas
transport material from the F star to its companion and back
again. However, the physical nature of the companion star
remained unclear in this model. Struve suggested that this is
a cold star which does not reveal itself in any way in radiation,
but has a mass not significantly smaller than that of the
primary star.

In 1961, the Italian investigator M. Hack suggested one
more hypothesis as to the nature of the system ε Aurigae. He
attempted to explain the contradiction embodied in the fact
that the radiation of the F star can produce in the atmosphere
surrounding the companion star an electron concentration of only
10^8 cm^{-3}, while a concentration of 10^{11} cm^{-3} is necessary to   <u>/87</u>
explain the observed absorption of $0.^m8$. Hack found, from a
careful investigation of the shapes of the absorption lines
from various levels, that the density of the ionizing radiation
must be 500 times greater than in Stromgren's model. This can
be explained by the fact that the dense gas and the envelope of
the companion itself becomes a source of radiation and ionization.

But the F star cannot produce radiation of the gas of the envelope in such an amount: its temperature (7000°) is too low. Another hotter source of radiation having a temperature of about 20,000° is necessary. Hack suggested that a hot B star with a radius of about 15 $R_\odot$ surrounded by an envelope 100 times larger than its radius (1 billion kilometers) serves as such a source. The distance between the centers of both stars in Hack's model is about 5 billion kilometers, and the masses of the components are 30 and 20 $M_\odot$. The B star is 6 times fainter than the F supergiant; therefore, its radiation does not reveal itself, even at minimum brightness (Figure 8c).

Successes in the study of the late stages of the evolution of stars of large mass have revealed new possibilities for explaining the puzzles of this system. Massive stars undergo catastrophic contraction (collapse) after complete exhaustion of their nuclear energy sources, and they are converted into black holes* — solid stars whose mass and gravitational fields are preserved but whose radiation cannot escape. Cannot the mysterious companion of the F star be a black hole? Such a hypothesis was advanced in 1969 by the American physicists V. Trimble and K. Thorne. From the standpoint of this hypothesis, the large mass of the invisible component, the existence of its surrounding envelope which absorbs the light of the F star, and the absence of any kind of characteristics of intrinsic luminosity are easily explained. A lively discussion about this problem unfolded at the end of 1970 and in 1971.

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*See Ya. B. Zel'dovich and I. D. Novikov's book, Black Holes in the Universe, Priroda, 1972, No. 4.

The well-known theoretician and cosmogonist A. Cameron, together with R. Stothers, decided to develop the hypothesis of Trimble and Thorne. Let us imagine that the invisible component has actually undergone collapse. Thus, part of its mass might have been ejected outwards. Judging from the comparatively small eccentricity of the orbit of the F star, only a small part of the mass was ejected — thousandths of a solar mass.

Already in 1964, the astronomer R. Mitchell discovered in ε Aurigae's spectrum the excess radiation in the infrared region which Kuiper and Felgett were unable to find 15 years before him. It corresponded to a temperature of an emitting object at 500° K in all. Since the energy of the F star radiation is 10^{39} erg/sec, solid particles can be heated up to such a temperature if they are located at a distance of 24 billion kilometers from the primary star. This means that the source of the radiation is a cloud of solid particles in the form of a disc or ring located at precisely such a distance from the F star.

Cameron attempted to explain the origin of the disc. He traced out the evolution of the orbits of dust particles surrounding both stars and concluded that the collapsar must have "intercepted" a large part of the particles from its more massive fellow and, therefore, it is the one, not the F star, which is surrounded by such a disc.

However, the Cameron-Stother hypothesis was soon subjected to criticism by the American astrophysicists P. Demarque and C. Morris. Having reviewed all the observational material about the ε Aurigae system, they arrived at the following scheme for its evolution. The system originated on the main

sequence (after passing through the prestellar stage and the gravitational contraction stage) as a pair of O stars — hot blue supergiants. The ratio of the masses of both stars was then two times larger than at present. The more massive star, having lost part of its mass, was converted into a F supergiant, and the less massive star, moving not far away from the main sequence, "selected" part of the mass ejected by the F star, and an opaque disc was formed around it from this material. The interior portions of the disc were completely ionized by the hot central star. The intermediate region consists of a strongly heated, that means, opaque to radiation, gas. Finally, the outer zone is transparent; it forms the spectrum of the envelope which is observed during the eclipse. It is characteristic that prior to the actual midpoint of the eclipse, lines of iron and other metals contained in the envelope disappear but the hydrogen lines are intensified and broadened. In the opinion of Demarque and Morris, this is the only appearance of component X in the system spectrum.

Now it is difficult to judge which of the hypotheses is nearer to the truth — the tempting hypothesis of Cameron-Stother, or the more "prosaic" hypothesis of Demarque-Morris. Only new investigations of this puzzling star will shed light on this question. However, it is completely clear that the study of stars which either have unusual structure (such as ε Aurigae) or are placed by their very nature in extremely favorable conditions for our observation (such as ζ Aurigae) may make a significant contribution both to astrophysics and to the physics of ultradense conditions and plasma physics associated with it.